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A new power generation method utilizing a low grade heat source*

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Abstract: Energy crisis make the effective use of low grade energy more and more urgent. It is still a worldwide difficult conundrum. To efficiently recover low grade heat, this paper deals with a theoretical analysis of a new power generation method driven by a low grade heat source. When the temperature of the low grade heat source exceeds the saturated temperature, it can heat the liquid into steam. If the steam is sealed and cooled in a container, it will lead to a negative pressure condition. The proposed power generation method utilizes the negative pressure condition in the sealed container, called as a condensator. When the condensator is connected to a liquid pool, the liquid will be pumped into it by the negative pressure condition. After the condensator is filled by liquid, the liquid flows back into the pool and drives the turbine to generate electricity. According to our analysis, for water, the head pressure of water pumped into the condensator could reach 9.5 m when the temperature of water in the pool is 25 °C, and the steam temperature is 105 °C. Theoretical thermal efficiency of this power generation system could reach 3.2% to 5.8% varying with the altitude of the condensator to the water level, ignoring steam leakage loss.

Key words: Low grade heat, Power generation, Condensation, Energy storage, Renewable energy
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1 Introduction

Because of the word wide energy shortage and the environmental pollution resulting from the large-scale use of fossil fuels, energy savings and renewable energy have received more and more attentions (Sargent & Lundy, 2003; Wiser and Bolinger, 2006; Li *et al*., 2008). There are rising energy demands in the developing world. It will increase carbon emission, which should be decreased (Quadrelli and Peterson, 2007; Ruhl, 2010). This has been intensified by the world economic crisis (Ruhl, 2010). Thus, improving the efficiency of energy units has become increasingly important (Li *et al*., 2008; Pazdzior, 2010). In addition to enhancing the efficiency of energy units, low grade heat utilization is another effective way to save energy (Abbott, 2009; Wang and Cao, 2009). Statistical investigations have indicated that wasted low grade heat accounted for 50% or more of the total heat generated in industry (Hung *et al*., 1997). Due to lack of efficient recovery methods, low grade heat has generally been discarded by industry, and has become an environmental concern because of thermal pollution (Anonymous, 2009). On the other hand, the amount of low grade natural energy on the earth is huge, such as geothermal energy and solar energy. Therefore, the recovery of waste heat and natural sources of low grade energy, with production of electricity, has become a challenging task for the power industry.

There have been many different technologies proposed to recover low grade heat, such as organic ranking cycles (Badr *et al*., 1990), nitinol heat engines (Ginell *et al*., 1979; Li, 1981), joule effect heat engines (Ginell *et al*., 1978), minto heat engines (Quickenden *et al*., 2004). However, widespread applications have not been achieved because of concerns about economic feasibility, safety, and

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environmental issues.

In this paper, a new method of power generation utilizing low grade heat is proposed and analyzed. The power generating system can operate if the heat source can provide the system with steam. Thus, the system can supply electricity, when the temperature of the heat source is little higher than the saturated temperature of the working fluid. As an example, if the working fluid is water, the system can be driven by a heat source with a temperature a little higher than 100 °C. If we adopt an organic fluid, the heat energy of heat sources with much lower temperatures could be utilized. Many low grade heat sources can supply steam above 100 °C, such as the boiler exhaust of power plant, heat steel slag in steel factory, solar flat-plate collectors. In this paper, we chose water as the working fluid. However, this method will still need to be testified further by experiments.

2 A hydro-electric power system driven by low grade heat sources

As shown in Fig. 1, the new power generation system is mainly composed of a steam generator, a condensator, and a turbine generator. The steam generator is driven by the low grade heat source. At the beginning, the condensator is opened to air and filled with air. When the steam is introduced into the condensator, the air is squeezed out, and the condensator will be filled with steam. Then the condensator is closed in and cooled, resulting in the sealed steam

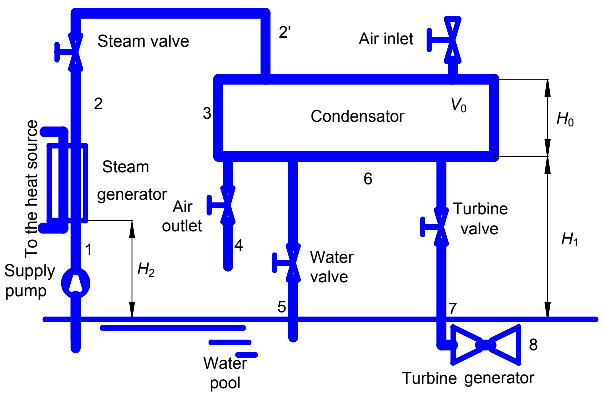

Fig. 1 Schematic of the new power generation system
H_0 is the height of the condensator, H_1 is the altitude of the condensator to the water pool, and H_2 is the altitude of the steam generator to the water pool

being condensed into water and leading to a negative pressure condition (Grew and Ibbs, 1952; Nag, 1981). Barna *et al.* (2010) reported a water hammer phenomenon induced by steam condensation. This phenomenon indirectly confirms that water can be pumped into a negative pressure condensator when it has been connected to the water pool (Grew and Ibbs, 1952; Nag, 1981; Rolle, 2000). Of course, a water hammer would not occur in our system, because water in the pipe and pool is initially immobile and can be controlled by valves. When the condensator is filled with water, one closes the water valve, opens the air inlet valve and the turbine valve, and water will flow back into the pool. When the water flows back, it drives the turbine to generate electricity.

However, there is a disadvantage of the new method. When operating, the condensator must be switched from filling water to releasing water. Thus, it cannot supply water continuously. This system generates power intermittently. To make the system generating power continually, we have to set a number of condensators to release water in turn. The condition is that the steam generator has the ability to supply steam for all condensators in turn.

From another view of point, it seems that the new system can store energy easily by converting the heat energy into gravitational potential energy. This is a great advantage compared with existing solar power systems (Al-Kharabsheh and Goswami, 2004), because heat energy is very difficult to store (Bell, 1981; Sargent & Lundy, 2003; Wiser and Bolinger, 2006; Boyle *et al.*, 2008). For some intermittent heat sources, such as solar energy, converting and storing heat energy in the style of gravitational potential energy is usually the best choice (Schmidt and Willmott, 1981).

3 Performance analysis

In the proposed method, the heat energy is converted into gravitational potential energy. No studies have been carried out to estimate the performance of this thermal process. Thus, we carried out a theoretical analysis of the thermal processes to estimate the theoretical performance.

There are many different thermal processes in the new power generation cycle. When steam is introduced into the condensator from the upper part, it

will meet air. When steam is cooled and condensed into water, air under steam will be disturbed by dripping water drops. If the water drops are little and very small, they can be ignored. If the flow of steam is very smooth, there must be an interface existing between the steam and the air, because steam is lighter than air. Based on these assumptions, condensation only occurs at the interface, and the temperature at the interface is the saturated temperature of water. Thus, above the interface, the condensator is filled by steam, and under the interface is air. Obviously, this process is irreversible and energy loss is brought about by condensation of steam at the interface (Nag, 1981; Rolle, 2000; Holman, 2002).

To estimate the performance, we have to know the amount of energy cost in the system (electricity cost from the water pump, and heat consumption of the steam generator), steam leakage or heat transfer between the steam and the air, and energy the system obtained (amount of water pumped into the condensator).

The amount of water can be determined by obtained water head in the condensator. The obtained water head is the difference between the environmental pressure and the final steam pressure in the condensator. According to thermal dynamics and fluid dynamics, this final steam pressure is the saturated pressure of water pumped into the condensator, when no incondensable gas such as air is mixed in the condensator. Thus, the final pressure is determined by the temperature of water, T_w. For example, saturated temperature of steam at 25 °C is about 3.2×10^3 Pa. The height of water level, H_{water}, in the condensator would be

$$H_{water}=(p_0-p_w)/(\rho_w g)-H_1, \tag{1}$$

where p_w is the saturated pressure of steam at temperature of T_w, p_0 is the atmospheric pressure, H_1 is the altitude of the condensator to the water pool as shown in Fig. 1, and ρ_w is the density of water. Thus, the volume, V_w, of pumped water is

$$V_w=V_0H_{water}/H_0, \tag{2}$$

where H_0 is the height of the condensator, and V_0 is its volume. If the efficiency of the tubular water turbine, η_T, and the efficiency of the generator, η_G, are given, the output electric energy, E_{out}, is

$$E_{out}=\eta_G\eta_T\rho_w gV_w(H_1+H_{water}/2). \tag{3}$$

To determine the volume of steam introduced into the condensator, we have to estimate the time of injecting process of steam first. It should be obtained by investigating the thermal process of steam and air in the condensator. Here the most complicated heat process is heat-transfer between the steam and the air in the condensator. Several assumptions are made:

(1) Ignore the pipe resistance of fluid flow; thus, the pressure of steam is the same as the environmental pressure.

(2) The wall of the condensator is adiabatic.

(3) Ignore water dripping; the liquid and gas flow is 1D and steady; however, the heat-transfer between steam and air is unsteady.

(4) When steam meets air in the condensator, its temperature at the interface is decreased to its saturated temperature.

Based on the above assumptions, the heat-transfer between steam and air is simplified into a problem of unsteady heat conduction in a semi-infinite body. Now we set the original point at the interface between steam and air, the x-axis is upward along the vertical direction. Thus, the temperature distribution in steam is (Incropera and Dewitt, 1985)

$$T_s(x,\tau)=(T_2-T_3)\mathrm{erf}\left(\frac{x}{2\sqrt{a\tau}}\right)+T_3, \tag{4}$$

where erf() is the error function. The heat flux is

$$q_s=\lambda\frac{(T_3-T_2)}{\sqrt{\pi a\tau}}, \tag{5}$$

where T_s is the temperature distribution in steam, T_2 is the initial temperature of steam, T_3 is the temperature of saturated steam at the interface, $a=\lambda/(\rho C)$, λ is the coefficient of heat conductivity, ρ is the density, C is the specific heat, τ is the time. At the beginning of steam introduced into the condensator, τ=0.

The temperature distribution in air is

$$T_a(x,\tau)=(T_0-T_3)\mathrm{erf}\left(\frac{-x}{2\sqrt{a\tau}}\right)+T_3, \tag{6}$$

and the heat flux is

$$q_a = \lambda \frac{(T_3 - T_0)}{\sqrt{\pi a \tau}}, \tag{7}$$

where T_0 is the initial temperature of air.

At the interface, there must be some steam condensed into water, and it can be calculated according to the energy conservation law:

$$m_{cs} = A \frac{q_s + q_a}{r_s}, \tag{8}$$

where A is the cross section area of the condensator, r_s is the latent heat of steam. When the condensator is filled with steam, the interface between steam and air must be moved from its top to the bottom. Thus, the volume of steam existing in the condensator is equal to the volume of the condensator:

$$m_s \tau_0 - \int_0^{\tau_0} m_{cs} \mathrm{d}\tau = V_C / v_s, \tag{9}$$

where m_s is the mass flow rate of steam, v_s is the specific volume of the steam, V_C is the volume of the condensator. According to Eq. (9), we can obtain the time, τ_0, when the condensator is filled with steam.

Thus, the heat consumption, Q_{in}, is

$$Q_{in}=m_s(h_2-h_1)t_s, \tag{10}$$

where h_1 is the enthalpy of water before the heat exchanger, and h_2 is the enthalpy of steam after the heat exchanger, t_s is steam supply time. Electric energy cost by the supply pump, E_{in}, is

$$E_{in}=m_s g H_2 t_s/\eta_p, \tag{11}$$

where η_p is the efficiency of the pump, m_s is the flow rate of the steam. The ideal thermal efficiency of the system, η_{ideal}, is

$$\eta_{ideal}=(E_{out}-E_{in})/Q_{in}. \tag{12}$$

According to above equations, the efficiency of the new power generation method can be theoretically calculated. Studies concerning parameters affecting performance of the system are required.

4 Theoretical model of a 1 MW power station

If we build a power station with a power, P, of 1 MW, and can supply electricity continually for 3 h, the volume of water, V_w, pumped into the condensator should be

$$V_w=2Pt_g/[\eta_G\eta_T\rho_w g(2H_1+H_{water})], \tag{13}$$

where t_g is the electricity supply time. Thus, the average mass flow rate of water, m_{water}, is

$$m_{water}=2P/[\eta_G\eta_T\rho_w g(2H_1+H_{water})]. \tag{14}$$

If the temperature of steam, T_2, is 378 K, other parameters can be obtained as shown in Table. 1. Results show that the system can provide a thermal efficiency of 4.8%.

Table 1 Parameters of the case of 1 MW power system

Parameter	Value
Power, P (kW)	10^3
Electricity supplying time, t_g (h)	3
Efficiency of the turbine, η_T	100%
Efficiency of the generator, η_G	100%
Efficiency of the supply pump, η_p	100%
Circulation pressure, p_2 (Pa)	1.01×10^5
Enthalpy of the steam, h_2 (kJ/kg)	2686.1
Specific volume of the steam, v_2 (m^3/kg)	1.7
Temperature of the steam, T_2 (K)	378
Saturated pressure of steam, p_w (Pa)	3.2×10^3
Mass flow rate of the steam, m_s (kg/s)	50
Saturated Temperature of water, T_3 (K)	373
Height of water level in the condensator, H_{water} (m)	4.97
Ideal thermal efficiency, η_{ideal}	4.8%
Enthalpy of the saturated water, h_3 (kJ/kg)	418.6
Atmospheric pressure, p_0 (Pa)	1.01×10^5
Atmospheric temperature, T_0 (K)	298
Enthalpy of water, h_1 (kJ/kg)	104.9
Density of water, ρ_w (kg/m^3)	1000
Temperature of water, T_w (K)	298
Gravitational acceleration, g (m^2/s)	9.81
Altitude of the condensator to the pool, H_1 (m)	5
Height of the condensator, H_0 (m)	5
Altitude of the heat source to the pool, H_2 (m)	0.5
Specific heat of the air, c_a (kJ/(kg·K))	1.007
Specific volume of the air, v_a (m^3·kg)	0.939
Time needed to fill the condensator with the steam, τ_0 (s)	1760
Volume of the condensator, V_0 (m^3)	1.5×10^5

We found that mass flow rate of the steam, m_s, was not sensitive to the thermal efficiency. The altitude of the condensator to the pool, H_1, was sensitive to the efficiency. Enhanced altitude, H_1, resulted in a higher efficiency from 3.2% to 5.8%, when H_1 increased from 0 to 10 m. This might be the most ideal situation. However, a higher altitude, H_1, resulted in a lower height of the condensator, H_0. Thus, to maintain the volume of the condensator, its floor area must be very large. In this case, floor area of the condensator was about 2.9×10^4 m^2 when H_1=5 m, and when H_1=1 m, it was about 1.67×10^4 m^2.

In the above case, the electricity supply time was 3 h, and about 30 min was required to fill the condensator with steam. To supply electricity for 24 h required eight condensators, and the heat source needed the ability to provide steam continually for 4 h to fill up eight condensators alternatively. These eight condensators could provide water flow alternatively for maintaining 24 h 1 MW electricity supply. Thus, the new power generation method shows its great advantage when the heat source is intermittent, such as with solar power.

5 Conclusions

This paper deals with a low grade heat utilizing method, which converts heat energy into gravitational potential energy of the working fluid, such as water or an organic fluid. The working temperature of the heat source could be a little higher than saturated temperature of the working fluid. For water, if the operating pressure is set as the environmental pressure, the working temperature of the heat source could be a little higher than 100 °C. For organic fluids, the working temperature might be much lower.

On this basis, a theoretical model of a 1 MW power generation system was established. Efficiency analysis showed that this system could perform at a thermal efficiency from 3.2% to 5.8%. Here the thermal efficiency of the system was increased with the increase in the condensator altitude, H_1. However, a higher altitude would lead to too large a floor area for the condensator, which would be very difficult to fabricate or assemble. Thus, we suggest H_1=5 m, and then the thermal efficiency is 4.8%.

A great advantage of the new power generation method is that, in this system, heat energy could be easily stored by converting it into gravitational potential energy. However, there are still some problems to be solved. For example, the 3D flow of the steam injecting process in the condensator was simplified as a 1D flow in this paper. This must be investigated further. At the end of the steam injecting process, there might be some air left in the condensator. Thus, the problem remains as to how to squeeze the air out of the condensator.

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